g Factor Measurements with Exotic Beams: a Sensitive Probe of Nuclear Structure Calculations

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Magnetic moments are most sensitive to single particle components in the wave function of nuclei as well as to their interplay with collective degrees of freedom. Because of the different sign of the spin g factors of protons and neutrons (g_s^p = 5.586 and g_s^n = -3.836), measurements of g factors of excited states enable the determination of their macroscopic structure. The combination of these measurements with those of $M1$ and $E2$ transition probabilities also provides stringent tests of theoretical models.

Measurements of this type can be used to address a number of issues of interest within the context of "RIA physics". First, in nuclei near closed shells, the g factor provides a good measure of the degree in which the wave function of specific levels can be associated with a pure shell model configuration. The shell model was found to work best in nuclei near closed shells such as ^{15}N, ^{17}O, ^{39}K, ^{41}K or ^{207}Pb, where moments close to the Schmidt lines have been measured. Similarly, measurements in odd nuclei around ^{132}Sn would provide the opportunity to assess the robustness of the shell model predictions for the description of the lowest excitations. Along the same lines, it is worth pointing out that predictions of drastic changes in the ordering of single particle levels in nuclei with a diffuse surface can also be checked by magnetic moment measurements. Another intriguing possibility deals with g factor measurements for the first excited states of even-even nuclei. In deformed nuclei, the gyromagnetic ratio usually has a value close or equal to the liquid drop estimate, e.g. $g_R = Z/A$. In very neutron-rich nuclei where a neutron skin is calculated to develop, it is predicted [1] that the neutrons in the diffuse skin will be associated with a spherical shape and, as a result, will no longer contribute to the magnetic moment. In contrast, the core of such nuclei is expected to remain deformed. Thus, the gyromagnetic moment then adopts the value $g_R = Z/(Z + N_{eff})$ where N$_{eff}$ is the number of neutrons in the core. By studying the g factor of the first excited state as a function of neutron number along an isotopic chain, evidence for the importance of the skin may be gathered.

Over the last 20 years, magnetic moments of short-lived nuclear states have been measured with the transient field technique. In its conventional application, target nuclei are excited by heavy-ion beams and are simultaneously ejected from the target material with high velocity. These fast ions then traverse a ferromagnetic material such as iron or gadolinium in which they interact with the polarized electrons. The net effect of the interaction is an effective hyperfine interaction at the nucleus which results in a precession of the angular distribution of the decay γ rays. This angular precession is directly proportional to the magnetic moment of the excited state under study.

More recently, an innovative approach to the technique has been proposed by a Bonn-Rutgers collaboration [2-4] which is particularly well suited to a use with exotic beams. Here, it is the beam that is Coulomb excited by a target nucleus. The target remains the same for all measurements, but excited states from different beams (a series of nuclei with the same Z, for example) can be studied. The technique uses projectile Coulomb excitation in inverse kinematics on a light target (see the discussion below for an example). After Coulomb excitation, the projectile then passes through the ferromagnetic material before stopping into a stopper. The thickness of the composite target is adjusted in such a way that the recoiling target nucleus, e.g. the partner in the reaction, escapes the target and is detected at zero degrees in a particle counter. The measurement is then a coincidence between the deexcitation gamma ray and the recoiling fragment in order to ensure that the alignement of the spin of the excited nucleus (which undergoes the precession) is carefully selected. The precession is extracted as usual from the ratio of intensities measured at carefully chosen angles. The main merit of this version of Coulomb excitation of an energetic beam of nuclei resides in the high efficiency of detection of deexcitation γ rays in coincidence with forward recoiling target nuclei. In addition to the kinematic focussing in the beam direction, the projectile ions have high velocities which are favorable since the transient field strength generally increases with the ion velocity. Furthermore, as stated above, the same target can be used for several beams, an approach which gets rid of systematic errors associated with the difficult preparation of different targets in the traditional technique of target excitation.

As an example of the technique, one can look at Ref. [2] where g factors are reported for the 2^+ and 4^+ levels of all even Se isotopes with mass A = 74-82. The experiments were performed with 230-262 MeV beams on a target which had the following composition. A layer of 0.95 mg/cm^2 of natural Si was evaporated on a 4.4 mg/cm^2 gadolinium substrate which was itself evaporated on a 1 mg/cm^2 tantalum foil backed by 1.35 mg/cm^2 of aluminum. In addition, a 7.5 mg/cm^2 copper foil was placed behind the target to stop the beam. The target and the beam stop were also mounted on a cooling rod to keep the assembly at a temperature of 50 K. Thus, in this experiment, the excited beam nuclei traverse the ferromagnetic layer and stop in the cubic environment free of further electronic interactions. The recoiling H-like Si ions had enough velocity to emerge from the beam stop and they were detected by a Si detector subtending an angle of +/- 13 degrees. The group has recently completed a series of measurements on the Zr isotopes with the same technique. The target in this case was titanium. Clearly, the target can be tailored to the specific need of the measurement. In fact, this summer the group will make a first attempt at performing the experiments with yet another configuration where backscatterd projectiles will be detected. This is an attempt to enhance the sensitivity of the technique to the shortest halflifes.

From discussions with N. Benczer-Koller it appears that experiments with good accuracy can be performed with beams of 10^8 particles per second in 3-4 days. This is from experience gathered with current experiments where the first excited states have energies around 0.5 MeV and the B(E2) values are not particularly large ($\sim$ 10-50 W.u.). Coulomb excitation calculations by C.J. Lister confirm this assesment as they lead to cross sections at the tens of mb level. We note that for very collective nuclei, where the excitation energies will be lower and the B(E2) probabilities will be larger, weaker beam intensities would still be useful and result in a good measurement.

Looking at the RIA beam intensity estimates, we can then see how far the technique can take us through a few examples.

-a- RIA will get closest to the drip line in the lighter nuclei. Hence, it is in these nuclei that effects associated with diffuse potentials will have a better chance to be observed. A cursory inspection of the yield curves indicates that important nuclei such as ^{32}Mg (shell inversion), or ^{42,44}S will be produced at the necessary 10^8 level.

-b- Kr isotopes are considered to be good examples of shape coexistence. Cases of large prolate *and* oblate deformation have been reported in the n-deficient nuclei. The n-rich nuclei are predicted to show very large, prolate deformations and, perhaps, first effects of diffuse surfaces for A $\sim$ 100 [1]. Intensities of 10^8 or better are calculated to be available for Kr from $A = 72$ to $A = 98$ or 100. In the presence of larger cross sections - as expected for the case of large deformations - 10^6 particles may suffice. This would enlarge the range by at least two mass units on the n-rich and p-rich sides.

-c- In the ANL "yellow" book the Zr isotopes are discussed at length as a very good case to follow the evolution of nuclear shell structure with mass. In this case studies would be possible from A $\sim$82 to A $\sim$ 104.

-d- In the heavy Sn nuclei, gyromagnetic ratios are experimentally within reach up to mass 136 or 137.

-e- The neutron-rich Ba nuclei are located in a deformed region exhibiting strong octupole correlations, and perhaps even octupole deformation. The region centers around ^{146}Ba. Here it would be of interest to measure g factors for the first few excited states of the yrast bands in the even-even isotopes and for the first few members of parity doublets in the odd nuclei. The calculated beam intensities are above 10^8 as far out as ^{150}Ba.

[1] W. Nazarewicz, private communication.
[2] K.-H. Speidel *et al.*, Z. Phys. A **342**, 17 (1992).
[3] K.-H. Speidel *et al.*, Phys. Rev. **C 57**, 2181 (1998).
[4] E. Ernst *et al.*, Phys. Rev. Lett. **84**, 416 (2000).